TRANSPORT PROPERTIES OF SLURRIES IN SIMULATED FRACTURE CHANNELS

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SUMMARY: This paper presents the results of a laboratory study of the transport properties of simulated ground drilling waste slurries in vertical channels. The effect of variables such as bulk velocity, solids concentration, particle size, fluid rheological properties and fracture width are presented. The most significant variables are particle size and fluid rheological properties. Bulk velocity and solids concentration were moderately influential, and slot width was found to be the less significant.

Introduction

Subsurface injection for waste disposal is widely produced, and many injection wells have been operating for years with massive volumes of material being injected. The major difference between such normal disposal operations and disposal of drill cuttings and impure mud is the high percentage of solid to be injected, with the corresponding requirement for injection above fracture closure pressure (Sirevag and Bale, 1993). Cuttings reinjection, when hydraulic fractures are created in subsurface strata to contain the drill solids, satisfies the environmental and economic criteria for achieving zero discharge of oily drilling waste. Cuttings reinjection is established practice in Alaska (Smith, 1991), the Gulf of Mexico (Malachosky et al., 1991) and recently has been employed in the North Sea (Minton, 1992). The initial proposal for cuttings disposal via subsurface injection involved creating a drilling cuttings/sea water slurry by first grinding the cuttings, then mixing with sea water to produce a pumpable slurry (Smith, 1991).

Since a process of downhole injection of drill cuttings was first developed in 1989, considerable research and engineering effort has gone into attempts to increase the effectiveness of these operations. Very little data is available to describe the particle size limitations on the cuttings slurry. Consequently a number of assumptions had to be made so as define the slurring mechanism. Two requirement exist. Firstly, to ensure that the solids remain suspended in the slurry in the annulus/tubing and near wellbore fracture while still pumpable or when pumping is halted; and secondly, to ensure that the particles are not large enough to bridge of across the face of the fracture. Properties of the slurry impacts on both the injection and fracturing operations. These properties should be studied in detail, since they give an indication of the ability of the slurry to suspend/transport solid particles.

Slurry Transport

It is extensively recognised that the flow behaviour of suspensions and slurries can be classified into two broad categories, namely homogeneous and heterogeneous. Homogeneous flow in a horizontal conduit flow is characterised by a uniform solids concentration across the conduit flow cross section. Solid particle additions to a very viscous carrier fluid or the addition of high concentrations of very fine particles (colloidal dimensions) to a thin carrier fluid usually produces a homogeneous slurry. For solid particles which are sufficiently large, dense and/or in a dilute state, settling will occur to various degrees so that the particles are not uniformly distributed and in horizontal flow, distinct a solid-concentration gradients exist along the vertical axis of the conduit. This slurry is categories as heterogeneous. The heterogeneous regime can be divided into several regions. If the velocity is sufficiently high, the solids approximately distribute uniformly over the cross section of the conduit. However, as the velocity decreases, the tendency of the particles to settle due to gravitational forces results in a non-uniform distribution of the solids in a vertical plane across the flow field. As the velocity decreases further, a point will be reached where the solids settle partially on the bottom of the conduit. The velocity at which this occurs will be called the critical deposit velocity. It is generally desirable to avoid this condition by operating at a velocity above the critical deposit velocity, since the presence of a deposit in the conduit promote plugging. A means of evaluating the solids distribution along the vertical axis of the conduit is extremely important in determining which mechanism controls the critical velocity of a given system (Wasp, 1970).

Although many flows may be clearly homogeneous or heterogeneous, many more are a combination of both, referred to as compound systems. It arises from the fact that in many systems, prior to transportation, the solids material are subject to some form of comminution (such as drill cuttings slurry). Finer particle size-fractions joint with the carrier fluid to form a homogeneous vehicle, while the coarse size-fractions are suspended heterogeneously in this vehicle.

Solids Distribution

The importance of predicting solids distribution in order to determine the degree of heterogeneity has been mentioned previously. The basic relationship governing particle dissemination in a two dimensional boundary layer at a steady state was proposed by O'Brien (1933), the rate of upward transport of the particles must be equivalent to the rate of fall due to gravity, which is expressed as follows:

$$CV_s + \varepsilon_s \frac{dc}{dy} = 0 \tag{1}$$

in which C is the volume concentration of solids at level y, and ε_s is a mass transport coefficient, assumed to be proportional to the momentum transport coefficient, ε_m:

$$\varepsilon_s = \beta \varepsilon_m \tag{2}$$

where β is a constant.

For two dimensional flow in a rectangular channel,

$$\tau = \tau_w \left(1 - \frac{y}{y_m}\right) \tag{3}$$

where τ_w is the shear stress at the boundary, and y_m is the vertical distance to the maximum velocity, i.e., the plane of zero shear. Thus,

$$\varepsilon_m = \frac{\tau(1 - y/y_m)}{\rho d_v / d_y} \tag{4}$$

Ismail (1952) evaluated the derivative of the velocity distribution from the Von Karman (1936) universal velocity defect law as:

$$\frac{v - v_{max}}{V_f} = \frac{1}{k} \log \frac{y}{y_m} \tag{5}$$

where v_{max} is the maximum velocity and $V_f = (\tau_w/\rho)^{1/2}$. Therefore, when dv/dy is evaluated from Equation (5), the result is

$$\varepsilon_m = kV_f y \left(1 - \frac{y}{y_m}\right) \tag{6}$$

or $\varepsilon_s = kV_f y\rho\left(1 - \frac{y}{y_m}\right)$ (7)

Inserting Equations (2) and (6) in Equation (1) and integrating, gives the following expression for the solids distribution ratio:

$$\frac{C}{C_A} = \left[\frac{y_a(y_m - y)}{y(y_m - y_a)}\right]^{V_s/\beta k V_f} \quad (8)$$

in which C_A is the solids concentration at some reference position y_a.

Wasp et al. (1977) have applied Equation (8) to a 12-inch-diameter pipe transporting coal slurries and suggested a criterion for transition from homogeneous to heterogeneous flow. Wasp et al assume that suspensions for which C/CA ≥ 0.8 are homogeneous, and heterogeneity is defined by C/CA ≤ 0.1. From Ismail's data (Ismail, 1952) on solids distribution at 8% and 92% of the distance across the centre line of the conduit, Wasp developed the following equation of C/CA from Equation (8):

$$\log\frac{C}{C_A} = -1.8V_s/\beta k V_f \quad (9)$$

Thus, having established the relationship for solids distribution ratio (C/CA) it is interesting to examine the influence of the variables of the fluid system on the predicted concentration profile.

Experimental Program

Description of Vertical Fracture Model

Figure 1 shows a schematic representation of the basic experimental rig design used in this study. It consists of three main components, i.e., a vertical fracture or slot flow model, fluid handling system and a Mono pump. The fracture model consists of two parallel perspex plates with dimensions 203.2 cm (6ft. 8in.) long, 45.72 cm

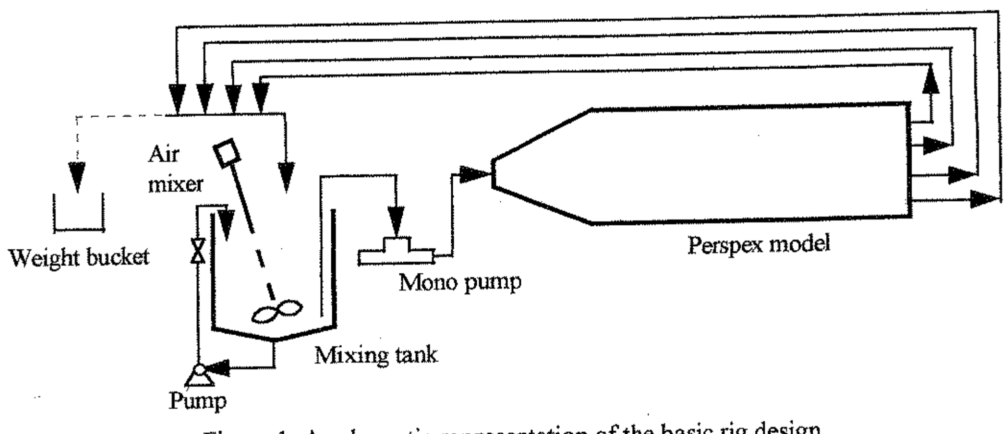

Figure 1. A schematic representation of the basic rig design.

(1.5 ft.) high, and the slot width can be varied between 6.35 mm (0.25 in.) and 12.7 mm (0.5 in.). This configuration allows both qualitative visual observations and quantitative solids concentration measurements for calculation of solids distribution ratio of slurry in the model. The mixing system consists of ~500 litre tank connected to a small pump which allows fluid to be circulated to the mixing tank to aid mixing prior to introduction to the model. An air mixer in the mixing tank is used for additional mixing. The fluid in the mixing tank can be pump to the fracture model at a variable speed by a Mono positive displacement pump capable of providing flow rates from 12 litre/min. to 70 litre/min. (or 0.05 bbl/min.ft. to 0.30 bbl/min.ft.). The volume flow rate and concentrations of slurry to the model were measured by diverting the flow stream into a 10 litre bucket and observing the time required for the collection of a specified volume and weight of the slurry. Seven sampling ports (with valves) were drilled at various positions over the cross section of the fracture model, which would allowed samples of the flowing slurry to be withdrawn. These sampling ports were approximately 183.2 cm downstream from the entrance and 20.0 cm before the exit.

The *in situ* solids concentration is measured by withdrawing samples of the flowing slurry from the fracture model at various positions over the cross section by opening the all valves of the sampling ports simultaneously when possible. Test samples of about one litre for each sample were taken from the sampling ports for a certain flow rate. The solids concentration of a sample may be adequately determined by taking a representative sample, weighing it wet, filtering, evaporating all water in an oven, and then re-weighing the dried sample. By difference the weight per cent solids was determined. From the known weight per cent solids contents of the test slurries and the densities of the solid and liquid, the volume percent solids was computed.

The experiments covered the effects of the solids concentration, fluid flow rate (bulk velocity), fluid rheology, particle size and slot width. Table 1 summarises the experimental variables covered in the present study.

Table 1. Experimental variables studied

Variable	Range of values
Slot width	0.653 - 1.27 cm
Solids concentration	8 - 32% by volume
Bulk velocity	6.8 - 34.1 cm/sec
Mean particle diameter (d_{50})	0.012 - 0.155 mm
Gel concentration	1.2 - 4.8 kg/m^3
Power law parameters	n = 0.24 - 0.55 k = 0.073 - 2.147 Pa.s^n

Description of System Studied

Simulated Ground Cuttings: Two grades of ground limestone were used as the dispersed phase during this study. Figure 2 shows their particle size distribution. These rock powders were used to simulate approximately two slurry systems of ground drill cuttings, which differed in fineness or particle size distribution. Hereafter these two slurry systems will be referred to as the fine and coarse slurry systems.

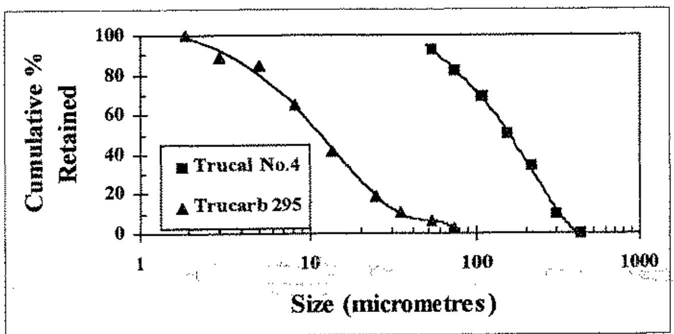

Figure 2. The size distribution for the two limestones powder samples used.

Base Fluid and Slurry Properties: Various concentrations of polymer solutions were used as a base fluid in this investigation. The polymer used in the test was xantan gum biopolymer (XCD), a commonly used polymer for fracturing gels. The concentration of polymer gel was selected so that a wide range of rheological properties of base fluid could be obtained. The rheological properties were measured using a Carri-med CS Rheometer, which provided viscosity data for the shear rates encountered in the slot. It was evident that the settling rates of the coarse portion of limestone particles in water were high, and this made it difficult to measure the viscosity and solids concentration along the test section. Therefore, in order to decrease the settling rate and to increase the length of time that particles were in suspension, most of the tests in this investigation were used XCD polymer solutions as the continuous phase.

Results and Discussion

Figure 3 shows the concentration profile of solids over the cross section of vertical fracture for various bulk velocity of slurry. As the velocity increases, the solids become uniformly distributed over the cross section of the fracture. However, as the velocity decreases, the tendency of the particles to settle due to gravitational forces results in a non-uniform distribution of the solids in the vertical plane across the flow field. The solids concentration curves of the lower velocity are slightly curved at the top of the section. Dividing the sample into different sizes, it is clear that the very fine portion will be more uniformly distributed than the coarser portions. The slight curvature at the top is believed due to size grading.

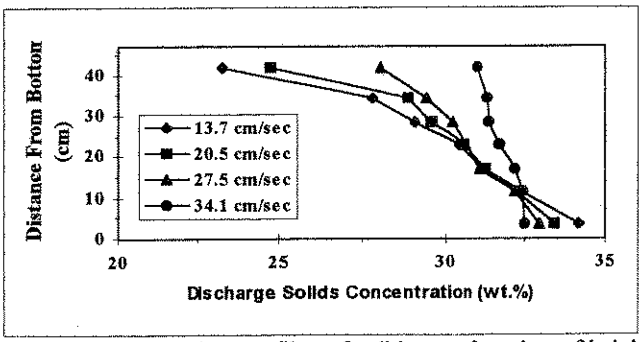

Figure 3. Concentration profiles of solids as a function of height.

Effects of Particle Size

Figure 4 shows the effect of the bulk velocity on the C/CA for the coarse portions of the coarse slurry system at a solids concentration of 16 volume percent and gel concentration of 1.8 kg/m^3 (15 lb_m/1000gal). The C/CA monotonically increases as the bulk velocity of the slurry increases. It shows that within the range of standard flow rate in the fracture for fracturing operation, the effect of increasing the velocity varies with particle size, but that the change in C/CA ratio is moderately significant. For the size fraction of mean particle diameter of 357.1 micron, doubling the velocity from 13.7 to 27.5 cm/sec changes the C/CA value from 0.83 to 0.87. For the size fraction of mean particle diameter of 252.1 micron the distribution ratio increases from 0.921 to 0.941 for the same velocity values.Figure 3 also shows that the particle size is of major importance in determining the degree of heterogeneity of a given system. For a given velocity, the coarser particle size, the lower the C/CA value. The dashed lines represent the calculated value using Equation (9).

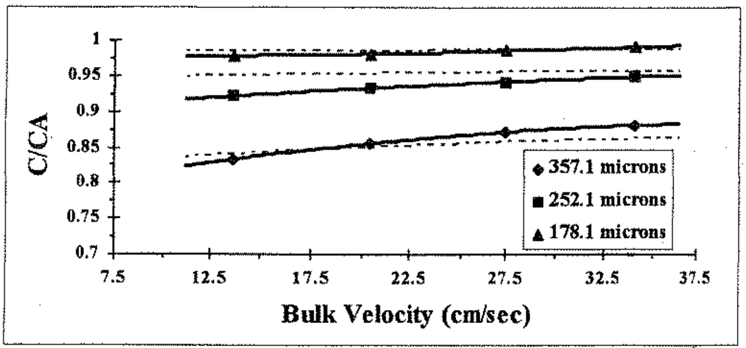

Figure 4. Effect of particle size on C/CA at Cv = 16% and gel conc. =1.8 kg/m^3 in 0.653 cm slot width.

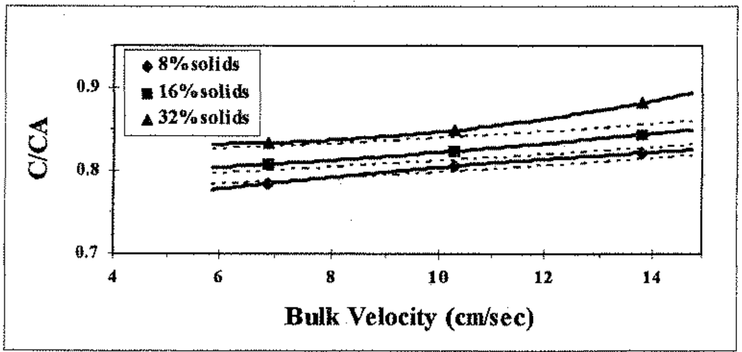

Figure 5. Effect of solids concentration on C/CA at gel concentration of 1.8 kg/m^3 in 1.27 cm slot width.

Effect of Solids Concentration

The effect of the solids concentration on the C/CA is of interest, since the concentration profile and drag force exerted by the fluid on the particles are functions of the solids concentration. Figure 5 shows the effect of the solids concentration on the C/CA for the size fraction of mean particle diameter of 357.1 micron of coarse slurry system at a gel concentration of 1.8 kg/m^3 (15 lb$_m$/1000gal). One observes in Figure 4 that for a given flow velocity, a higher solids concentration gives a higher C/CA value. This trend is reasonable since by increasing the solids concentration, the concentration profile becomes more uniform and the particle drag becomes larger.

Effects of Rheological Properties

Increasing the gel and slurry concentrations has the effect of increasing the slurry viscosity. This increased viscosity tends to reduce the size of the turbulent fluctuations but also to reduce by a greater degree the actual settling velocity of the suspended particles. Figure 6 illustrates the effect of gel concentration on the C/CA of the mean particle diameter of 357.1 microns. The wide range of rheological properties of these base gels is shown in Table 2. Clearly at low velocity (13.7 cm/sec), the system changes from a heterogeneous condition at 0.9 kg/m^3 (7.5 lb$_m$/1000gal) gel concentration to a homogeneous condition at 1.8 kg/m^3 (15 lb$_m$/1000gal) gel concentration. As expected, the higher viscosity of a base fluid allows particles to stay in suspension longer, resulting in a higher C/CA. Base gel properties can be tailored to efficiently transport drill cuttings slurry at low bulk velocities when necessary.

Effects of Slot Width

Two combinations of slot width was studied. In the normal range of bulk velocities, the difference in C/CA is slight This is shown in Figure 7 for a velocity of 13.7 cm/sec, gel concentration of 1.8 kg/m^3 (15 lb_m/1000gal) and 16 volume percent of solids. The distribution ratio (C/CA) is dependent on slot width, the C/CA slightly decreases as the slot width increases. Much greater velocities were required for the larger slot width. As can be seen in Figure 7, the slot width has a minor influence on the C/CA. Changing the slot width from 0.635 cm to 1.27 cm changes, the C/CA value by 1.7%.

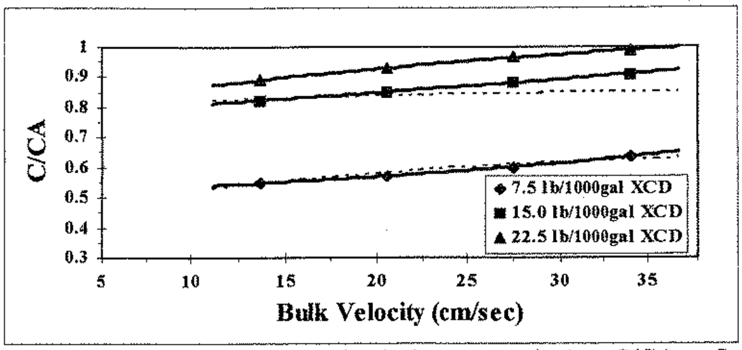

Figure 6. Effect of Rheological Properties (gel concentration) on C/CA at Cv = 8%.

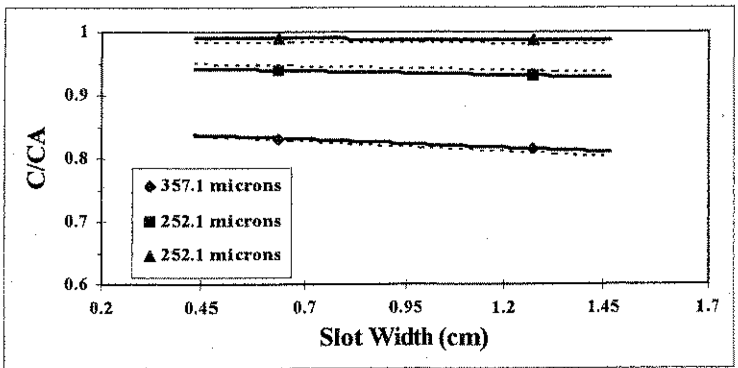

Figure 7. Effect of slot width on C/CA at Cv = 8% and gel conc. =1.8 kg/m^3.

Conclusions

The following conclusions are based on the results obtained in steady state particulate slurry transport in simulated fracture channels:

1. The most important factors controlling suspension stability of slurry are particle size and rheological properties.
2. As the particle size increases, the C/CA efficiency decreases. For systems containing a broad particle size distribution, the fine particles are constituted in a pseudohomogeneous non-Newtonian vehicle, in which the coarser portions are transported as an asymmetric heterogeneous suspension.
3. The C/CA efficiency increases as fluid viscosity increases.
4. Bulk velocity and solids concentration has a moderate influence on the suspension stability of the slurry.
5. Slot width has a slight effect on the suspension stability of slurry.

Acknowledgements

The authors wish to thank to the University of Technology, Malaysia and University of Nottingham, U.K for their financial support in this project.

References

Ismail H.M. (1952) Turbulent Transfer Mechanism and Suspended Sediment in Closed Channels. *Trans., ASCE*, Vol. 117, pp. 409-446.

Malachosky E., Shannon B.E. & Jackson J.E. (1991) Offshore Disposal of Oil-Based Drilling Fluid Waste: An Environmentally Acceptable Solution. SPE Paper 23373, presented at the 1st. Int. Conf. of Health, Safety and Environment, The Hague, Netherlands, pp. 465-473.

Minton R.C. & Secoy B. (1992) Annulus Re-injection of Drilling Wastes. SPE Paper 25042, presented at the EUROPEC Conference, Cannes, France, November 16-18, pp. 247-253.

O'Brien M.P. (1933) Review of the Theory of Tubulent Flow and Its Relation to Sediment-Transportation. *Trans., Am. Geophysical Union*, Vol. 14, pp. 487-491.

Sirevag G. & Bale A. (1993) An Improved Method for Grinding and Re-injection of Drill Cuttings. SPE Paper 25758, presented at the SPE/IADC Drilling Conference, Amsterdam, February 23-25, pp. 773-778.

Smith R.I. (1991) The Cuttings Grinder. SPE Paper 22092, presented at the SPE International Arctic Technology Conference, Anchorage, Alaska, May 28-31.

von Karman T. (1934) Turbulence and Skin Friction. *Journal of the Aeronautical Sciences*. Vol. 1-2, pp. 1-20.

Wasp E.J. Aude T.C. Kenny J.P. Seiter R.H. & Jacques R.B. (1970) Deposition Velocities, Transition Velocities, and Spatial Distributions of Solids in Slurry Pipelines. Hydrotransport 1. First Int. Conference on the Hydraulic Transport of Solids in Pipes. University of Warwick, September 1-4, pp. 53-76.

Wasp E.J. Kenny J.P. & Gandhi R.L. (1977) Solid-Liquid Flow Slurry Pipeline Transportation. Trans Tech Publication, Clausthal, Germany.